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### **Carderock Division**

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Technical Report

## **Are the Energy Analysis (EA) and the Statistical Energy Analysis (SEA) Compatible?**

by

G. Maidanik

K. J. Becker

[Work supported by ONR and In-House Fundings.]

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## ABSTRACT

Originally the statistical energy analysis (SEA) was restricted to low coupling loss factors, at least, lower than the corresponding loss factors of the (adjunct) dynamic system to which the externally driven (master) dynamic system was coupled. The coupling loss factors of reference are those from the adjunct dynamic system to the master dynamic system. Something happened on the way and this restriction was lost and never examined again, at least, until now. With the advent of structural fuzzies, as introduced by Soize and subsequently interpreted by a number of researchers, questions relating not only to the validity of the conservation of energy arose, but also arose were questions relating to the coupling loss factors, to the loss factors and to the external input powers. In trying to decipher, in terms of (SEA), some of these questions, a number of surprising answers emerged which casts doubts on the universal validity of (SEA). In this vein, for example, the authors of this report have written a few papers defining and redefining various loss factors. These authors found that the definitions of loss factors are as elusive as are the definitions of radiation efficiencies. Both, loss factors and radiation efficiencies, are parameters that require redefinitions in order to convince the noise control engineers that they are using them correctly when engaged in a particular noise control task. To do otherwise invites misrepresentations and false claims. In small part this report attempts to warn the noise control engineers that as valuable as (SEA) is, it has fundamental limitations and that these limitations are not merely and strictly a question of frequency regions; i.e., high-, mid- and low-frequencies, even though it is recognized that some of the limitations, herein considered, may be relieved by introducing these frequency divisions on the validity of (SEA).

## INTRODUCTION

This report is a paper intended for oral delivery at the 26<sup>th</sup> Meeting of the Acoustical Society of America in Austin, Texas and constitutes a part of a key-note address to be given in TBL Noise Class at the Boeing Company in Seattle, Washington.

Sketched in the first viewgraph (V1) is an externally force-driven isolated dynamic system - the *master* dynamic system. The accounting of the response of this dynamic system is conducted in terms of an energy analysis (EA). In this analysis the external force-drive is stated in terms of the external input power  $\Pi_e^o(\omega)$ , which is a function of the frequency  $(\omega)$ ;  $(\omega)$  is the center frequency of a band of width  $(\Delta\omega)$ . The response is stated in terms of the energy  $E_o^o(\omega)$  stored in the master dynamic system. The master dynamic system is defined in terms of the loss factor  $\eta_o(\omega)$ , the modal density  $\nu_o(\omega)$  and the mass  $(M_o)$  [1-3]. The loss factor  $\eta_o(\omega)$  relates the power dissipated in the master dynamic system to the energy  $E_o^o(\omega)$  stored in that dynamic system; namely

$$\Pi_o^o(\omega) = \eta_o(\omega)[\omega E_o^o(\omega)] \quad .(1a)$$

The conservation of energy (power) demands that the dissipated power be equal to the external input power  $\Pi_e^o(\omega)$ ; namely

$$\Pi_e^o(\omega) = \Pi_o^o(\omega) \quad .(1b)$$

The modal density  $\nu_o(\omega)$  is the number of modes per unit frequency in the master dynamic system [3]. It follows that the number of modes  $N_o(\omega)$  that resides within the frequency bandwidth  $(\Delta\omega)$  in this dynamic system is given by

$$N_o(\omega) = \nu_o(\omega) \Delta\omega \quad . (2)$$

From Equations (1) and (2) the modal external input power  $\pi_e^o(\omega)$ , the modal power  $\pi_o^o(\omega)$  dissipated and the modal energy  $\varepsilon_o^o(\omega)$  stored may be cast in the forms

$$\Pi_e^o(\omega) = N_o(\omega) \pi_e^o(\omega) \ ; \ \pi_o^o(\omega) = N_o(\omega) \pi_o^o(\omega) \ ; \ E_o^o(\omega) = N_o(\omega) \varepsilon_o^o(\omega) \quad , (3)$$

respectively.

The master dynamic system is now coupled to an adjunct dynamic system; the coupling may be either mass control  $(m_c)$ , stiffness control  $(k_c)$ , gyroscopically control  $(G)$  or any combination thereof [3,4]. A question arises: What is the influence of this coupling either on the response of the master dynamic system, on the response of the adjunct dynamic system or on the response of the dynamic system as a whole (master + adjunct) [5]? One of the major influences is that a number of loss factors may be appropriately defined [5-8]. As Equation (1) initiated, an appropriate loss factor is one that relates a definitive stored energy to a definitive dissipated power. In turn, the dissipated power must be balanced in a conservation of energy (power) equation.

Sketched in the second viewgraph (V2) are a number of appropriately defined loss factors among them the induced loss factor ( $\eta_I$ ). These loss factors, as already stated, relate stored energies to corresponding powers dissipated [1-8].

In the third viewgraph (V3) the conservation of energy (power) is imposed and some of the relationships among various loss factors are stated. Central to some of these relationships is the definition of the global coupling strength  $\mathfrak{I}_o^s(\omega)$  [1-3]. The global coupling strength is the ratio of the stored energy  $E_s(\omega)$  in the adjunct dynamic system to the corresponding stored energy  $E_o(\omega)$  in the master dynamic system

$$\mathfrak{I}_o^s(\omega) = [E_s(\omega) / E_o(\omega)] \quad . (4)$$

Significantly, it is found that the ratio of the induced loss factor  $\eta_I(\omega)$ , in the master dynamic system, to the indigenous loss factor  $\eta_s(\omega)$ , in the adjunct dynamic system, is equal to the global coupling strength  $\mathfrak{I}_o^s(\omega)$ ; i.e.,

$$\mathfrak{I}_o^s(\omega) = [\eta_I(\omega) / \eta_s(\omega)] \quad , (5)$$

where  $\mathfrak{I}_o^s(\omega)$  is defined in Equation (4).

Sketch in the fourth viewgraph (V4) is the transference from the global to the modal coupling strength; the modal coupling strength is related to the global coupling strength by merely the ratio of the modal density  $\nu_o(\omega)$  of the master dynamic system to the modal density  $\nu_s(\omega)$  of

the adjunct dynamic system, respectively [3]. Explicitly this relationship is

$$\zeta_o^s(\omega) = [\nu_o(\omega)/\nu_s(\omega)] \mathfrak{I}_o^s(\omega) \quad .(6a)$$

An induced modal overlap parameter  $b_I(\omega)$  for the master dynamic system and an indigenous modal overlap parameter  $b_s(\omega)$  for the adjunct dynamic system are defined

$$b_I(\omega) = \nu_o[\omega \eta_I(\omega)] \quad ; \quad b_s(\omega) = \nu_o[\omega \eta_s(\omega)] \quad .(7)$$

Then from Equations (5), (6a) and (7) the modal coupling strength  $\zeta_o^s(\omega)$  may be cast in the form

$$\zeta_o^s(\omega) = [b_I(\omega)/b_s(\omega)] \quad .(6b)$$

(The modal overlap parameter  $\{\nu(\omega)[\omega \eta(\omega)]\}$  simply states the ratio between the frequency width  $[\omega \eta(\omega)]$  of a typical mode to the corresponding typical frequency distance  $[\nu(\omega)]^{-1}$  between neighboring modes [3].)

In the fifth viewgraph (V5) it is pointed out that a "smoothed out" induced loss factor  $\langle \eta_I(\omega) \rangle$  is independent of  $\eta_s(\omega)$ ; notwithstanding that  $\eta_I(\omega)$  exhibits modal undulations, that pertain to modes in the adjunct dynamic system, for values of  $b_s(\omega)$  that are less than unity. [3,5-15] It



is thus concluded that the "smoothed out" value of the modal coupling strength  $\langle \zeta_o^s(\omega) \rangle$  exceeds unity if

$$\langle b_l(\omega) \rangle > b_s, \quad (7a)$$

and is less than unity if

$$\langle b_l(\omega) \rangle < b_s. \quad (7b)$$

(It is to be understood that what is called here the smoothed out value of a quantity is commensurate with Skudrzyk's mean-value for this quantity [10].)

Sketched in the sixth viewgraph (V6) is the derivation of the modal coupling strength  $\zeta_o^{sea}(\omega)$  in terms of the statistical energy analysis (SEA) [1-3]. It is argued that  $\zeta_o^{sea}(\omega)$ , by definition, remains less than unity. Indeed

$$\zeta_o^{sea}(\omega) = \eta_{os}(\omega) [\eta_{os}(\omega) + \eta_s(\omega)]^{-1} < 1 \quad (8)$$

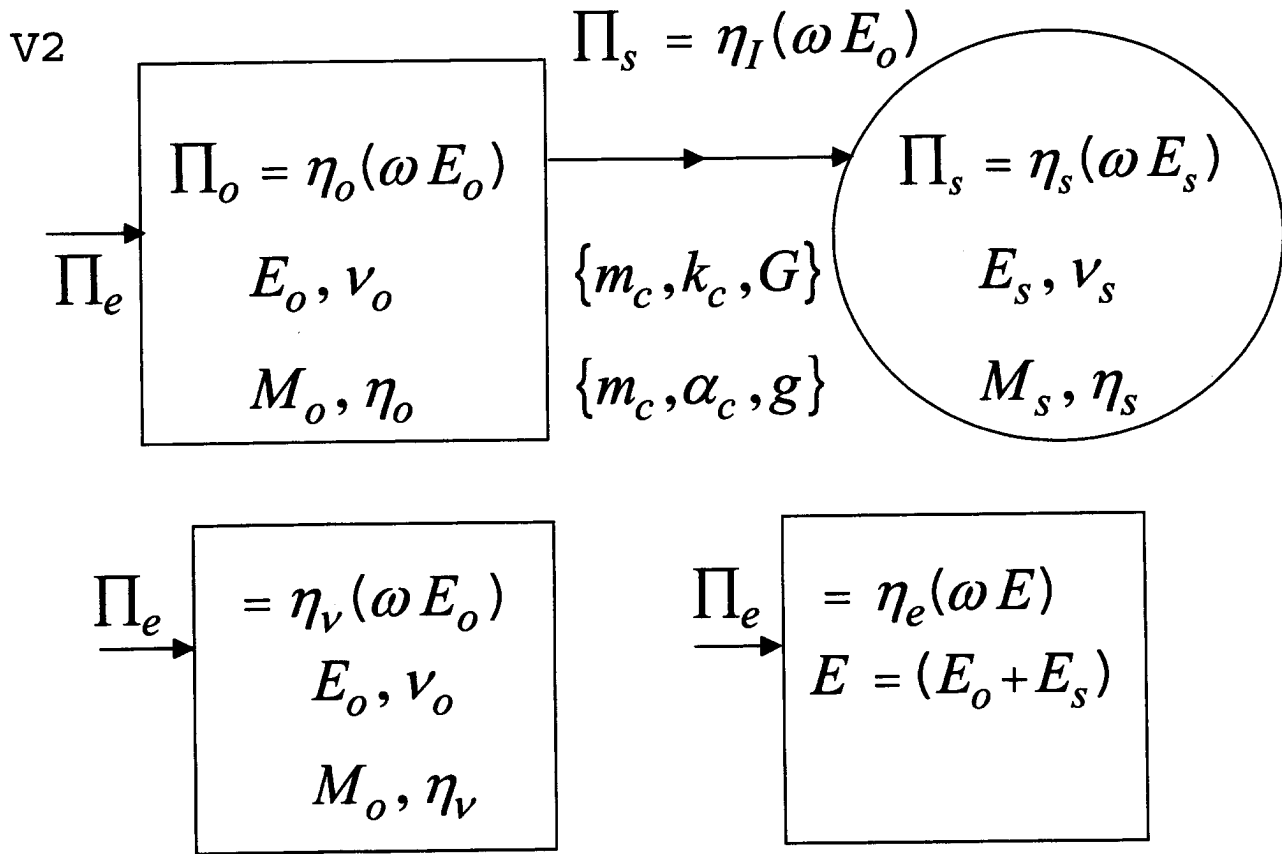
The seventh viewgraph (V7) again emphasizes that the modal coupling strength  $\zeta_o^{sea}(\omega)$  in SEA, by definition, is less than unity;  $\zeta_o^{sea}(\omega) < 1$ . On the other hand, the modal coupling strength  $\zeta_o^s(\omega)$  in EA is not so restricted. Then, in order for  $\zeta_o^s(\omega)$  to be compatible with  $\zeta_o^{sea}(\omega)$ , the modal overlap parameter  $b_s(\omega)$  of the adjunct dynamic system must exceed

the smoothed-out induced modal overlap parameter  $\langle b_I \rangle$  of the master dynamic system;  $b_s(\omega) > \langle b_I \rangle$ . [cf. Appendix B.] To validate (SEA),  $\langle b_I \rangle$  serves as a lower threshold for  $(b_s)$ .

$$\begin{array}{c} \Pi_e^o \longrightarrow \boxed{\begin{array}{l} = \Pi_o^o = \eta_o(\omega E_o^o) \\ E_o^o, \nu_o \\ M_o, \eta_o \end{array}} \end{array}$$

$(\eta_o)$  the loss factor of the master  
dynamic system

The master dynamic system is coupled to an  
adjunct dynamic system resulting in the  
definition of a number of loss factors,  
among them the induced loss factor  $(\eta_I)$



$\eta_s$  the loss factor of adjunct dynamic system

$\eta_v$  the virtual loss factor of the coupled master dynamic system

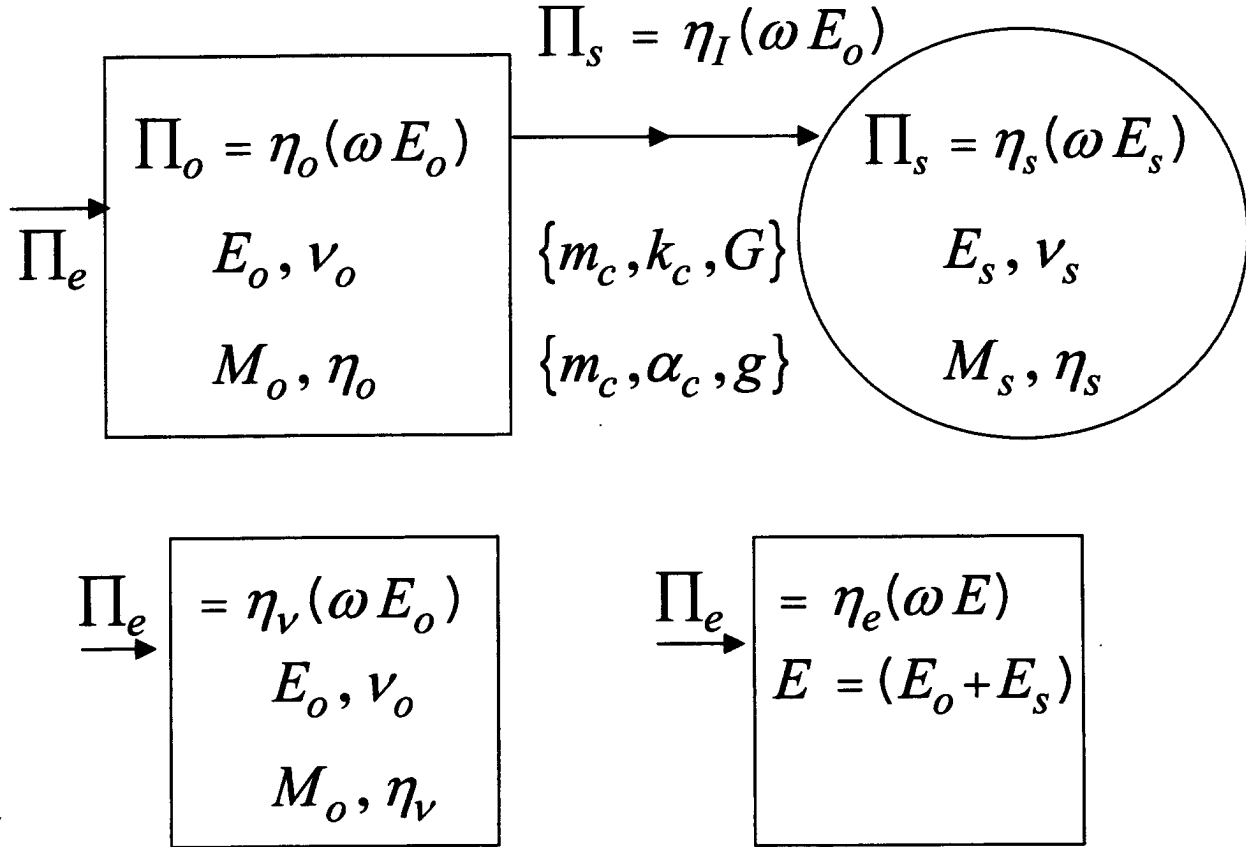
$\eta_e$  the effective loss factor of the coupled dynamic system (master + adjunct)

$$\Pi_s = \eta_I(\omega E_o) = \eta_s(\omega E_s)$$

$\eta_I$  the induced loss factor of the master dynamic system; induced by the coupling.

The Conservation of Energy (Power)  $\Pi_e = \Pi_o + \Pi_s$

and the relationships among some loss factors

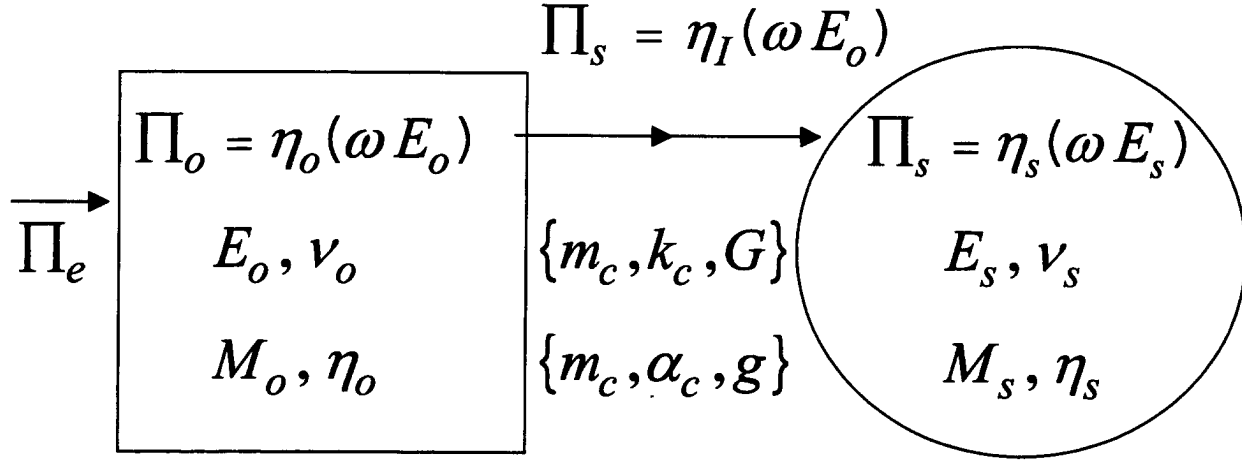


$$\eta_v = \eta_o + \eta_I \quad ; \quad \eta_v = \eta_e(1 + \mathfrak{I}_o^s) \quad ; \quad \mathfrak{I}_o^s = (E_s / E_o)$$

$\mathfrak{I}_o^s$  the global coupling strength

$$\eta_I(\omega E_o) = \eta_s(\omega E_s) \quad ; \quad (\eta_I / \eta_s) = \mathfrak{I}_o^s$$

The modal coupling strength and the modal overlap parameter



$$\Pi_s = \eta_I(\omega E_o) = \eta_s(\omega E_s) ; \quad \mathfrak{I}_o^s = (E_s / E_o) ; \quad (\eta_I / \eta_s) = \mathfrak{I}_o^s$$

$\mathfrak{I}_o^s$  the global coupling strength

$$(\nu_o / \nu_s) \mathfrak{I}_o^s = \zeta_o^s \quad ; \quad (\nu_o / \nu_s) (\eta_I / \eta_s) = (b_I / b_s) = \zeta_o^s$$

$\zeta_o^s$  the modal coupling strength

$(b_I) = [\nu_o(\omega \eta_I)]$  the induced modal overlap

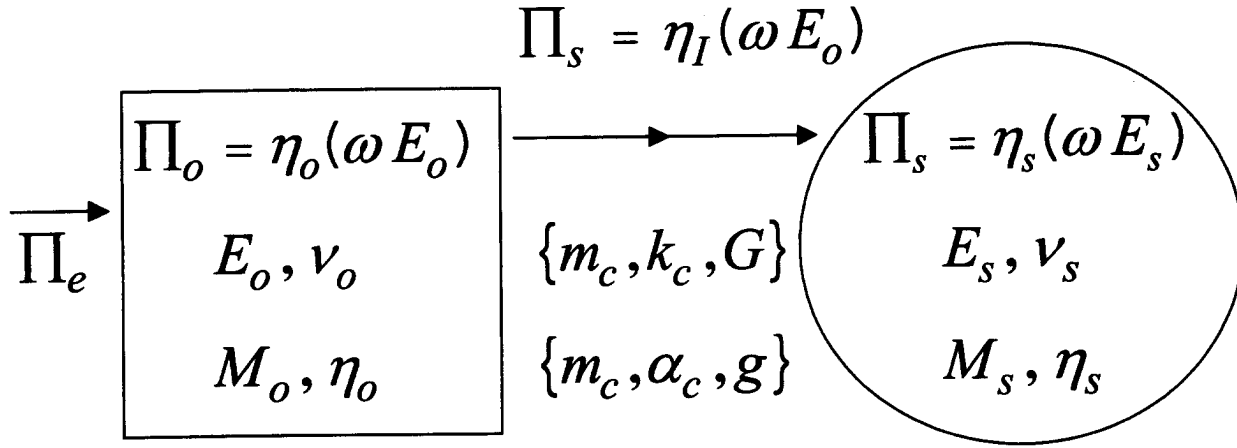
parameter of the master dynamic system

$(b_s) = [\nu_s(\omega \eta_s)]$  the modal overlap parameter of

the adjunct dynamic system

V5

The "smoothed out" induced loss factor  $\langle \eta_I \rangle$



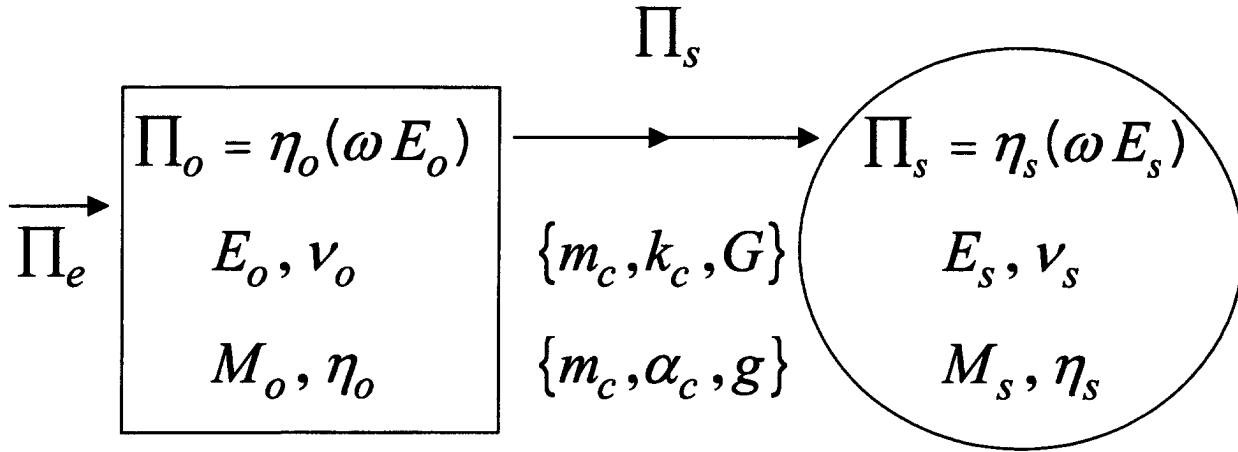
It is found that  $\langle \eta_I \rangle$  is independent of  $(\eta_s)$  although the modal undulations in  $(\eta_I)$  are dependent on  $(\eta_s)$  through the value of  $(b_s)$ . There are no modal undulations in the adjunct dynamic system if  $b_s \geq 1$ .

Thus  $[\nu_o(\omega \langle \eta_I \rangle)] [\nu_s(\omega \eta_s)]^{-1} = (\langle b_I \rangle / b_s) = \langle \zeta_o^s \rangle$

There is no restriction on the value of  $\langle \zeta_o^s \rangle$  ; noting that  $\langle \eta_I \rangle$  is the larger, the stronger the coupling. If the coupling is strong and the loss factor  $(\eta_s)$  of the adjunct dynamic system is small,  $\langle \zeta_o^s \rangle$  may exceed unity.

V6

Under SEA



$$\eta_s(\omega E_s) = \Pi_s = [\eta_{so}(\omega E_o) - \eta_{os}(\omega E_s)]$$

Hence

$$(\eta_s + \eta_{os})(\omega E_s) = \eta_{so}(\omega E_o) \quad ; \quad \mathfrak{J}_o^{sea} = (E_s / E_o)$$

$$\mathfrak{J}_o^{sea} = \eta_{so}(\eta_s + \eta_{os}) \quad ; \quad (\eta_{so} / \eta_{os}) = (\nu_s / \nu_o)$$

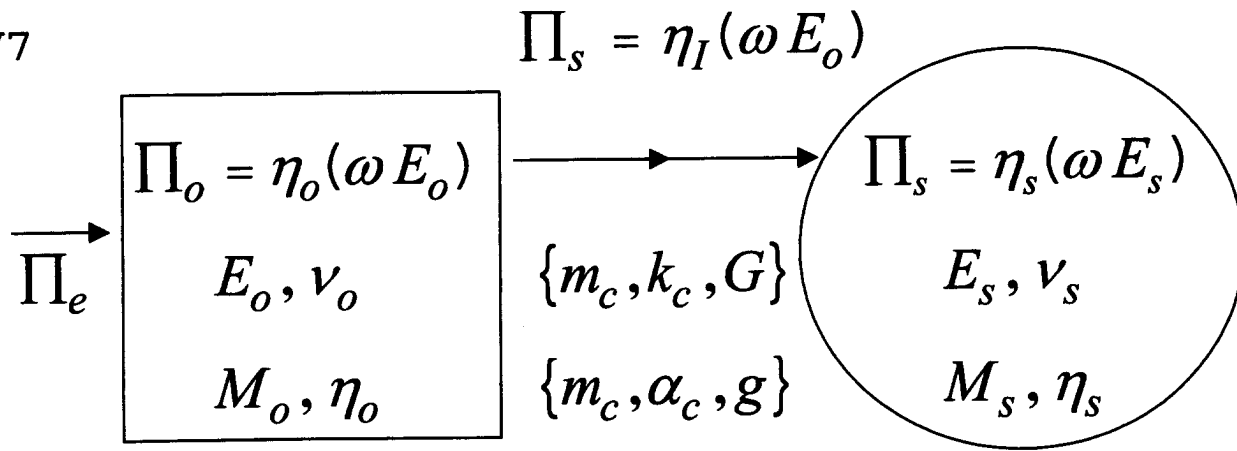
$$\zeta_o^{sea} = \eta_{os}(\eta_{os} + \eta_s)^{-1} < 1 \quad ; \quad \mathfrak{J}_o^{sea} = (\nu_s / \nu_o) \zeta_o^{sea}$$

Again

$$\zeta_o^{sea} < 1$$



V7



A tenet of SEA

$$\eta_s(\omega E_s) = \Pi_s = [\eta_{so}(\omega E_o) - \eta_{os}(\omega E_s)]$$

$$\zeta_o^{sea} = \eta_{os}(\eta_{os} + \eta_s)^{-1} < 1$$

A tenet of EA

$$\eta_s(\omega E_s) = \Pi_s = \eta_I(\omega E_o) \quad ; \quad \langle \zeta_o^s \rangle = (\langle b_I \rangle / b_s)$$

Thus for  $\zeta_o^{sea}$  and  $\langle \zeta_o^s \rangle$  to be compatible ( $b_s$ ) must exceed  $\langle b_I \rangle$ . Then  $\langle b_I \rangle$  constitutes a threshold for ( $b_s$ ) to validate SEA;  $\langle b_I \rangle < b_s$ .

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## Appendix A

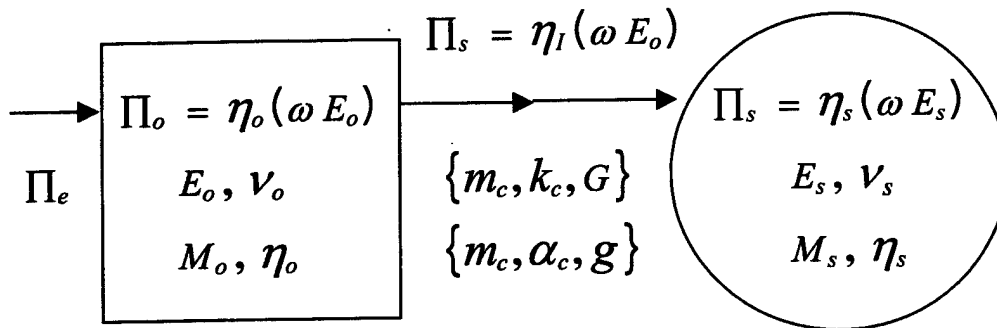
The modal coupling strength in SEA is shown to be the relationship

$$\zeta_o^{sea} = \eta_{os}(\eta_{os} + \eta_s)^{-1} < 1 \quad . (A1)$$

Using the relationship in SEA

$$\langle \eta_I \rangle (\omega E_o) = \eta_s (\omega E_s) = \Pi_s = [\eta_{so} (\omega E_o) - \eta_{os} (\omega E_s)] \quad , (A2)$$

taken off the figure below



one finds the equivalent to Equation (A1) in the form

$$(\langle \eta_I \rangle / \eta_{so}) = \eta_s (\eta_{os} + \eta_s)^{-1} < 1 \quad . (A2)$$

It is noted that both  $\langle \eta_I \rangle$  and  $(\eta_{so})$  are dependent on the strength of the coupling between the master dynamic system and the adjunct dynamic system. Moreover, from Equation (A2), were the coupling loss factor  $(\eta_{os})$ , from the adjunct dynamic system to the master dynamic system, small compared with the

loss factor ( $\eta_s$ ), of the adjunct dynamic system;  $\eta_{os} \ll \eta_s$ , the smoothed-out induced loss factor is largely equal to the coupling loss factor ( $\eta_{so}$ ) [16]. The coupling loss factor ( $\eta_{so}$ ) accounts for the transfer of power from the master dynamic system to the adjunct dynamic system.

## Appendix B

One may state the relationship between the virtual loss factor  $(\eta_v)$  and the effective loss factor  $(\eta_e)$  in the form

$$\eta_v = \eta_e(1 + \mathfrak{I}_o^s) \quad ; \quad \eta_v = (\eta_I + \eta_o) \quad ; \quad \mathfrak{I}_o^s = (\eta_I / \eta_s) \quad . (B1)$$

From Equation (B1) one may derive

$$(\eta_e - \eta_o)(\eta_s - \eta_e)^{-1} = (\eta_I / \eta_s) = \mathfrak{I}_o^s \quad . (B2)$$

Since  $(\mathfrak{I}_o^s)$  is positive definite (including zero) it follows that:

$$\text{If } \eta_s > \eta_o \quad ; \quad \eta_s > \eta_e > \eta_o \quad , (B3a)$$

and

$$\text{if } \eta_s < \eta_o \quad ; \quad \eta_s < \eta_e < \eta_o \quad . (B3b)$$

On the other hand, if the adjunct dynamic system is a *sink*; defined such that  $\mathfrak{I}_o^s \equiv 0$ , then

$$\eta_e \Rightarrow \eta_v = \eta_I + \eta_o \quad ; \quad \eta_e > \eta_o \quad . (B4)$$

From Equations (B3a) and (B4) one finds that

$$\eta_s > \eta_o + \eta_I > \eta_o \quad . (B5)$$



In this case ( $\eta_I$ ) is the additional loss factor that is acquired by the master dynamic system due to its coupling to the sink. Equation (B5) merely states that an adjunct dynamic system that qualifies as a sink would possess a loss factor that exceeds that of the master dynamic system when *coupled* to that sink [17].

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